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Material Failure and the Growth of Instabilities in Hollow Cylindrical Samples of Aluminum Shocked to 14Gpa and 50 Gpa

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Abstract

Understanding the surface stability of metals undergoing dynamic fracture at shock breakout is important to several applications in metals processing. The advantages of using the Pegasus II facility to investigate the phenomena occurring at shock break out are described. As an example of the data collected, we concentrate on brief descriptions of two experiments that compared the tensile failure, i.e. "spall", patterns in the presence of sinusoidal perturbations seeded on the free inner surface of cylindrical samples made of structural grade Al 6061-T6. These samples were subjected to ramped waves with shock pressures of 14 GPa and 50 GPa to observe the effect of pressure on the production of a type of volumetric failure that is termed here "microspall." This failed region behind the exiting surface of the shock wave is comprised of a significant volume of low-density, probably granular, material. The failure mechanism, combined with the forces that cause inertial instability, leads to rapid pattern growth in the failed material, observable as density variations, as well as to pattern growth on the surface. Pattern growth was observed to vary with perturbation amplitude, wavelength, and shock pressure. Both increased pressure and increased amplitude were shown to destabilize a stable perturbation. Increasing the wavelength by a factor of 3 was shown to result in significantly slower growth of the pattern within the failed volume. The mechanisms leading to the formation of the spall volume and to the patterns are discussed briefly.

I. PEGASUS II FACILITY

Understanding the surface stability of metals undergoing dynamic fracture at shock breakout is important to applications in metals processing including explosive hardening and forming, impact cratering, and the development of impact-resistant materials. In the last two years, we have conducted a series of experiments on the Pegasus II microsecond z-pinch facility at Los Alamos National Laboratory. The goal of these experiments was to study instabilities generated at the surface of metals by the break out of high-pressure shocks. The shock is generated on the outer surface of the target by the collision of a collapsing Al 1100-O liner driven by an axial current. The Pegasus II facility produces a cylindrically-convergent shock wave which, by its nature, has no "edge effects" propagating from side walls and which has less than 1% azimuthal variation. In addition, the pressure is highly reproducible and easily varied within a range of 14-50 GPa without reconfiguration of the apparatus; hence the choice of shock pressures in these experiments. The cylindrical geometry and EM drive allow for an extensive diagnostics suite to report the current delivered to drive the liner, the collision time, and the subsequent behavior of the target. The diagnostics include 4 axial x-ray images for each shot, up to 5 radial images, laser backlighting, and optical cameras to record the shock-driven self-emission of the gas fill. Each of these diagnostics can be timed independently. A detailed diagram of the diagnostics suite is available in an earlier report.[1] A sketch of the target appears in Fig. 1.

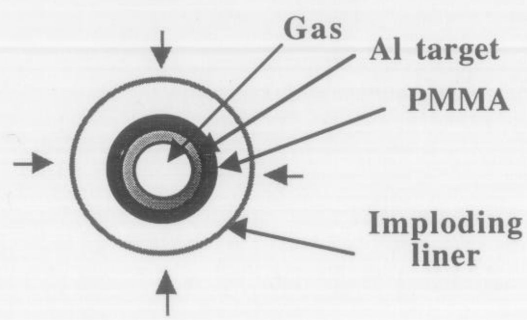

Figure 1. The cross-section of a typical target. An aluminum cylinder of 3-mm thickness is surrounded by 2 mm of plastic and gas-filled with 1 atm of Xe or Ar. The imploding liner of the z-pinch, made of .4 mm thick Al collides with the target at 1.5 km/sec. Various perturbations are inscribed on the inside surface of the Al target.

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II. TWO EXPERIMENTS

As an example of the data our team has produced on this machine, let us look at the results of two experiments designed to study the spall patterns and instabilities that grow on cylinders shocked at 14 GPa and at 50 GPa. Of particular interest is the effect that varying amplitudes and wavelengths would have on these patterns. The static axial image of the target shot at 14 GPa is shown in Fig. 2. The experiment in Fig. 2 was composed of a cylinder of Al 6061-T6 of height 17.5 mm, i.d. 20 mm, and thickness 3 mm. The target was encased in a 2 mm Lucite (PMMA) holder, and was filled with 1 atm of Xe gas. The purpose of the Xe gas is to monitor the passage of the shock, both in axial x-ray images which capture the increased Xe density at shock passage, and by recording the self-emission of the shocked Xe by optical cameras. The Lucite holder shapes the shock into a ramped Taylor wave; without this holder, the shock would have a square-wave shape. Inscribed parallel to the axis of symmetry on the inner surface were 13 wavelengths of 8° (1.4 mm) wavelength, 60 μm amplitude sinusoids and 9 wavelengths of 8° wavelength, 120 μm amplitude sinusoids. Markers were placed to indicate the original phase by marking the angle where one of each of these wavelengths protruded into the gas in the static setup.

Figure 3 shows the radiograph taken at 3.38 μs after the liner collides with the Lucite holder. The shock wave is clearly visible in the Xe gas. In the aluminum, two broad bands of low-density "micro-spalled" material have appeared, separated by a stripe of high density material. On the inner surface of the aluminum cylinder, there is a high-density "crust". Instabilities have grown in regions adjacent to both the inscribed patterns. In the region where the 120 μm perturbations were inscribed, the pattern has disrupted the crust, and material is clearly visible extending inside the radius of the crust and up to the edge of the shock in the Xe. The phase of the perturbation in this area has also inverted and now the marker points to a region that points away from center. We conclude that the region containing 120 μm perturbations is "unstable" and that the 60 μm region is "stable". Nevertheless, the 60 μm perturbations have generated very significant density perturbations within the aluminum, and "stable" is not an adequate description of the degree of pattern formation.

The geometry of the the experiment at 50 GPa was similar. The experiment retained the 13 wavelengths of 8° (1.4 mm) wavelength and 60 μm amplitude sinusoids; however, preliminary calculations showed that these would become unstable at 50 GPa. As a result it was decided to replace the region containing 120 μm amplitude sinusoids with longer wavelengths that calculations showed would develop slowly. This region then had 4 wavelengths of 24° (4.2 mm) wavelength and 60 μm amplitude. Another difference between the two experiments is the use of 1 atm Ar as the gas fill in the 50 GPa experiment. While Ar does not allow x-ray imaging of the shock wave in the gas, it improves discrimination between low-density Al and compressed gas in the dynamic images.

The 8°, 60 μm amplitude perturbations were observed to form rapidly as the rarefaction wave swept back through the Al. In Fig. 4a, taken while the rarefaction wave is still in the Al, the pattern in the microspall associated with the longer 24° wavelength is hardly noticeable. Later in time, however, the longer wavelength pattern becomes more distinct and perturbs the inner crust of Al in the last image, taken at 2.77 μs after liner impact. The 8° wavelength, which was termed "stable" in the 14 GPa experiment, is clearly "unstable" under 50 GPa; distinct "spikes" have formed even in the earliest image.

III. Pattern Formation Mechanism

Although the details of individual patterns are not well produced by the 2-D code CALE which has been used to design these experiments, we have found that CALE predicts the gross features and the degree of "stability" of the patterns. By analyzing the process taking place in these simulations we suggest that this failure is fundamentally a multiple spall or "scabbing" process that is usually observed to produce slab-like layers[2]. However, the steep shape of the release behind the shock front causes the "layers" that break off to have a size in the 10's of microns, hence the name "microspall". This size coincides with the grain size of the aluminum, and it is to be expected that neither the shock front nor the material response is uniform at this length scale. Thus, there are significant 3-D perturbations that probably result in the formation of 3-D "rubble" of distributed size and irregular shapes. These effects are, of course, beyond the modeling capabilities of the 2-D code. The direct capture and analysis of the "rubble" would be illuminating.

The pattern in the microspalled material is formed by the shape of the rarefaction wave which is set by the surface structure. Azimuthal velocities of the cast-off material are alternately convergent and divergent, dependent on the direction of the normal of the rarefaction wavefront. The speed of the broken-off material is proportional to the pressure of the shock.

The inner "crust" of Al is due to the finite front width of the shock and is predicted by CALE simulations where it retains strength in "stable" perturbation growth. The forces that lead the crust to break up in the formation of fingers are still being analyzed.

IV.Summary

We have observed the failure process termed "microspall" in Al 6061-T6 and the formation of pattern growth within this failed material at various shock pressures. The failure mode is associated with the Taylor-like shock release shape. These experiments show that pattern growth can be seeded by small-amplitude perturbations on the inner surface of the Al. The growth rate has been shown in these two experiments to be dependent on amplitude, wavelength, and shock pressure.

V. REFERENCES

[1] E.A. Chandler, et al., "Use of the Pegasus Z-Pinch Machine to Study Inertial Instabilities in Al: A preliminary reoport" in *Proc. of the 6th International Workshop on the Physics of Compressible Turbulent Mixing,* G. Jourdan and L. Houas, eds., Marseille, Impremerie Caractere, 1997, p.111.

[2] Johnson, W,. **Impact Strength of Materials**, Crane, Russak New York (1972), p. 67 ff.

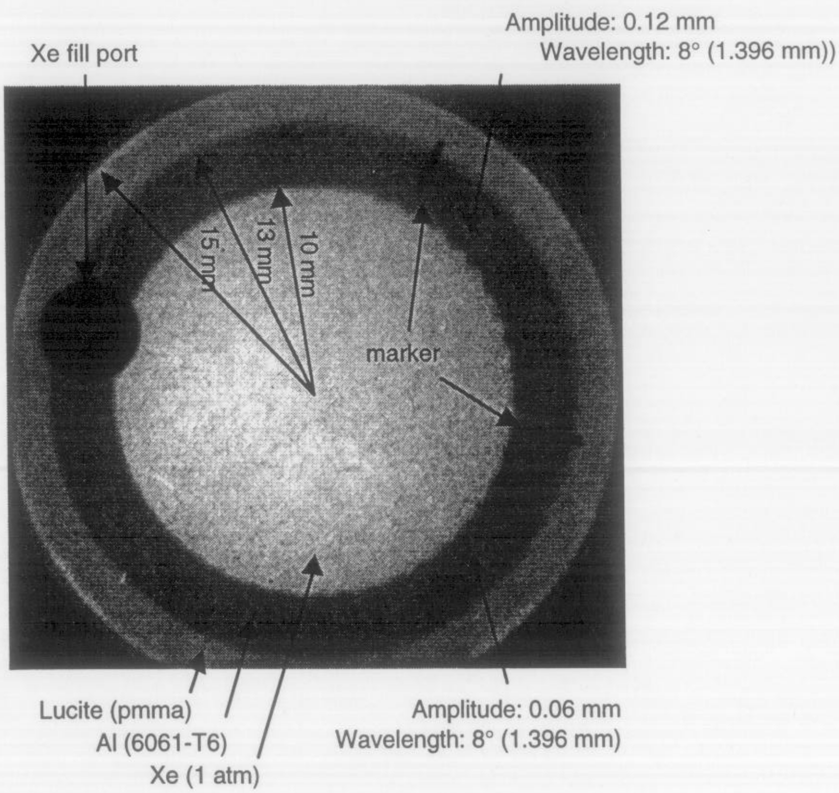

Figure 2. The static axial x-ray image of the target used for the 14 GPa experiment. On the inner surface are inscribed two sinusoidal patterns—one with several wavelengths of 8° (1.4 mm) wavelength, 0.12 mm amplitude in the upper right quadrant, and another with 8° (1.4 mm) wavelength, 0.06 mm amplitude wavelengths in the lower right quadrant. The 50 GPa target is similar except that 24° (4.2 mm) wavelength , 0.06 mm sinusoids are substituted in the upper right quadrant. Also, the Xe gas fill used in the 14 GPa target is replaced with Ar for better resolution of the inner Al surface.

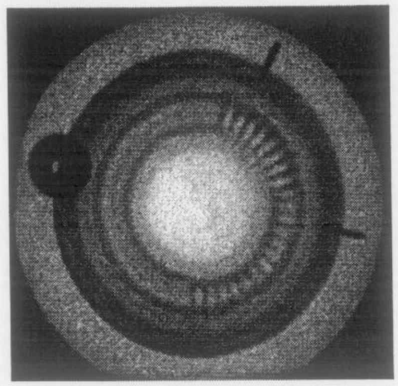

Figure 3. The axial x-ray image of the 14 GPa target taken at 3.66 μs after liner impact. The growth of the perturbations is clear. Perturbations of 0.06 mm amplitude have resulted in a "stable" pattern, while perturbations of 0.12 mm amplitude have resulted in a pattern with distinct spikes protruding into the gas-filled region; this pattern is "unstable".

a *b* *c* *d*

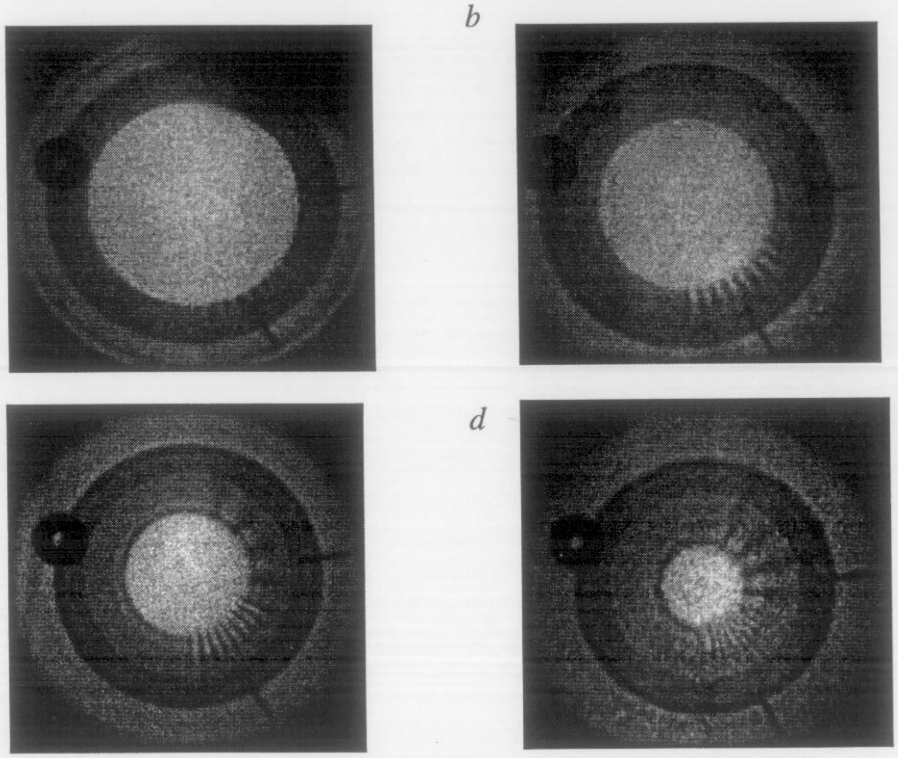

Figure 4. Axial x-ray images of the 50 GPa experiment taken in succession at times a) 0.99 b) 1.55 c) 2.16 d) 2.77 μs after liner impact to compare the growth rate of the perturbations of 1.4 and 4.2 mm wavelengths, both with 0.06 mm amplitude.